# Studies on the Resonant, Combusting Flow Phenomena in a Small-Scale Quartz Glass Valveless Pulsejet Engine by High-Speed Flame Imaging using Chemical Tracers

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***Abstract*— The pulsejet, as a small-scale propulsion module, has great potential, and finds many applications, particularly in micro air vehicles. The valveless pulsejet engine has no moving parts and so has many attributes for scaling down for such applications. Presently, the design of a pulsejet is carried out by empirical methods in the absence of accurate physics-based prediction models. Evolving a design methodology calls for a clear understanding of the complex resonant combusting flow. Optimization of the critical parts such as the inlet aerodynamic valve, combustion chamber and exhaust pipe calls for a clear understanding of the coupled flow structures and movement of the flame front inside the pulsejet engine. Hence, an experimental study using high-speed imaging, of the internal operation of an ingeniously constructed fully transparent inline intake quartz glass valveless pulsejet engine has been carried out. Using a fully transparent engine and by capturing the complex coupled flame and flow structures has resulted in a better understanding of the flow physics of resonant combustion inside a pulsejet engine. The transparent quartz glass valveless pulsejet engine has been specially designed and fabricated and successfully test run with hydrogen as the fuel to observe the unsteady flame front movement. Since a hydrogen flame is non-luminous, chemical tracers were specially developed to enhance the luminosity of the hydrogen flame and thus improve its visibility in order to track the movement of the heat release zones. The non-intrusive flame imaging technique developed has been successfully demonstrated in capturing the resonant, combusting flow field in an inline intake valveless pulsejet engine.**

***Key words* – Pulsejet engine, resonant combustion, thermo acoustics, luminosity, toroidal vortices**

## I. Introduction

High speed photography is an important non-intrusive optical technique, well suited for understanding the unsteady, coupled flow and heat release phenomena inside a valveless pulsejet engine. The pulsejet engine, which is a simple thermo-acoustic propulsion device, does not have any rotating/moving elements inside it. The inherent characteristic of possessing static thrust is an added advantage of such an intermittent propulsion device. However, the working of such an engine is still not well understood and hence most of the designs are still made on an empirical basis. A clear understanding of the working of such engines by any improved method of non-intrusive flow visualisation will enhance the knowledge base and will ultimately help in establishing a sound design methodology. Hence, studying the entire engine's coupled flame/flow structures was essential to understand the sustained working of the engine. A pulsejet's basic components are the inlet, combustion chamber, and tailpipe. Although the valveless pulsejet engine can operate with both liquid and gaseous fuels, ignition and mixing of a gaseous fuel has been found to be relatively easy. Generally, to start an engine and to attain self sustained pulsations, a small amount of compressed air is forced into the inlet at an angle while the gaseous fuel is being injected. The mixing of the fuel and air and the necessary creation of the required turbulence results in ignition and thus start of the sustained pulsations. The fuel/air mixture explodes in the small combustor volume, which results in the sudden expansion of the gases both through the exhaust pipe and the inlet pipe. When these gases exhaust their momentum mainly rearward, the partial vacuum created in the combustion chamber sucks in fresh air from the inlet and residual hot gases from the exhaust duct (Kadenacy effect). The residual hot gases from the exhaust pipe ignite the fresh air / fuel mixture and the repeated pulsations occur signifying resonant combustion (fig.1). Pressure oscillations in the pulsejet are attributed to the self excitation of Rayleigh coupled duct acoustics and mixing-controlled combustion-heat release resulting in a limit-cycling behavior. Thus for continuous, sustained operation of the pulsejet engine, there should be a correctly tuned duct acoustics combination of the inlet pipe, combustion chamber and the tailpipe dimensions. The dimensions and even the shape of these parts play a crucial role for an optimal design of the pulsejet engine. The natural frequency of oscillation is mainly determined by the effective length of the exhaust-gas tailpipe, but the fuel and oxidizer input rates also influence the sustained combustion behavior.

This paper reports the results of high-speed imaging of the resonant combusting flow in a hydrogen fuelled inline intake valveless pulsejet engine. Potassium iodide, barium iodide and strontium iodide tracers were used in the study. Solutions of these salts in ethanol were prepared and used as tracers. These tracers enhanced the luminosity of the hydrogen flame and were successfully used in the studies. Luminosity variation can be considered as an indication of the instantaneous chemical

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reaction rate and hence can even be a base to track the movement of the heat release zones.

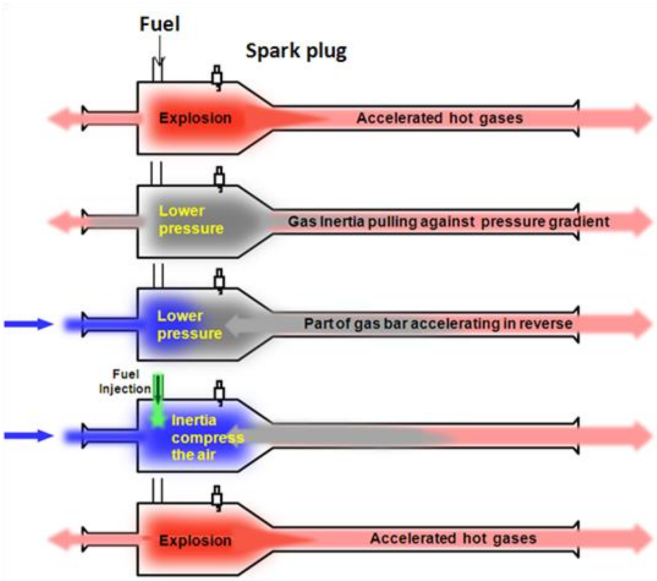


Fig.1 Sequence of events related to resonant combustion inside an inline intake valveless pulsejet engine.

## II. DEVELOPMENT OF CHEMICAL TRACERS

A pure hydrogen flame is non-luminous and hence it is difficult to capture the flame fronts at high frame rates in high-speed photography. The tracers used in the present study were inexpensive, safe and easy to handle. A method of using chemical tracers and enhancing the hydrogen flame luminosity has been demonstrated successfully. Chemical tracers had to be specially developed which met the following criteria (i) it should help to illuminate the hydrogen flame in low concentrations, (ii) the medium in which the tracer is dissolved / mixed should not interfere with the combustion process and (iii) both the tracer and solvent should be safe to handle.

The standard concept of flame tests practiced in chemistry was adopted. The flame test is used to visually determine the identity of an unknown metal or metalloid ion based on the characteristic color the salt turns the flame of a Bunsen burner. The heat of the flame excites the metals ions, causing them to emit visible light. The characteristic emission spectra can be used to differentiate between some elements.

According to the concept of flame tests, salts of potassium, barium and strontium gives lilac to red, apple green and crimson red flames respectively during a flame test. Since, the corresponding salts have to be soluble in a solvent that does not interfere with combustion and at the same time be environmentally friendly, ethanol was selected as the solvent. The chemicals selected were potassium iodide, barium iodide and strontium iodide.

## III. EXPERIMENTAL DETAILS

Fig. 2a. shows the dimensional details of the inline intake valveless pulsejet engine and fig. 2b. shows the hardware of the metal engine and the quartz glass model of the pulsejet engine employed for the study. The metal engine model was made of mild steel and the fuel injector was a stainless steel tube of diameter 6.4 mm with 4 feed holes of 0.8 mm diameter. The engine was first run using a metal model for determining the operational envelope and to establish the operating frequency of the engine, so that the capture frame rate could be correctly ascertained.

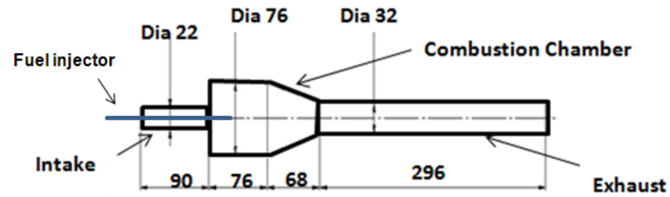


Fig.2a Inline intake valveless pulsejet engine with dimensions (Dimensions in mm)

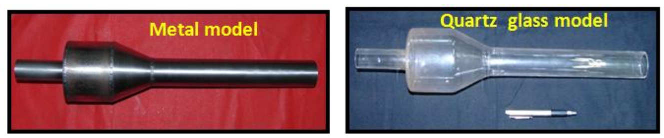


Fig. 2b. Metal and quartz glass engine models

Fig. 3a shows a typical result of the metal model. The sustained regular pressure oscillations signifying resonant combustion is to be noted. The FFT (fig. 3b) shows that the dominant frequency was around 250 Hz. The regulated hydrogen gas was fed into the injector from a cylinder using a SWAGELOK regulator. The injection pressure was always maintained around 0.69 MPa. The fuel line had a non-return valve and flame arrester and the fuel was controlled by a 6 mm SWAGELOK needle valve; the fuel mass flow was measured with a MICROMOTION mass flow meter. The unsteady pressure signals and the fuel mass flow were recorded with a Data Acquisition System. The ignition of the hydrogen that was fed into the engine was achieved by an external source (fig.5).

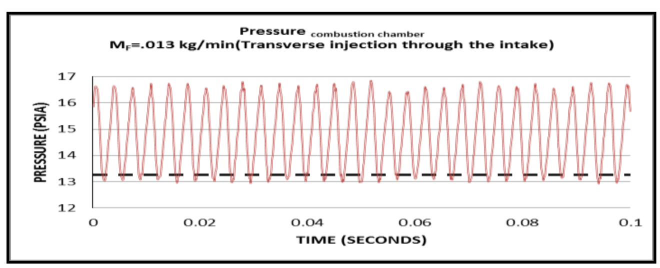


Fig. 3a Typical result of the unsteady pressure signal showing resonant combustion

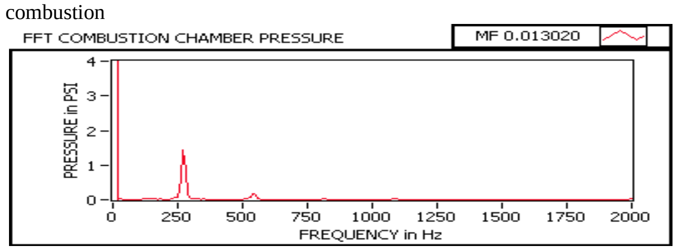


Fig. 3b FFT showing the dominant frequencies

An exact replica of the metal model of the inline intake valveless engine model was made with quartz for visualisation studies. Fig.4. shows a schematic of the test setup. For the quartz engine models the fuel was injected through the inlet with the stainless steel injector having 4 feed holes of 0. 8 mm diameter. Two schemes of testing with the tracers were explored. Initially, the tracers were injected manually, with the help of a syringe, into the combustion chamber after igniting the engine with gaseous hydrogen fuel. A second method was also tried with the tracer being siphoned in by the hydrogen injection itself. Both the methods worked successfully. Fig.5 shows the details of fuel injector that was used for the experiments and the quartz engine mounting.

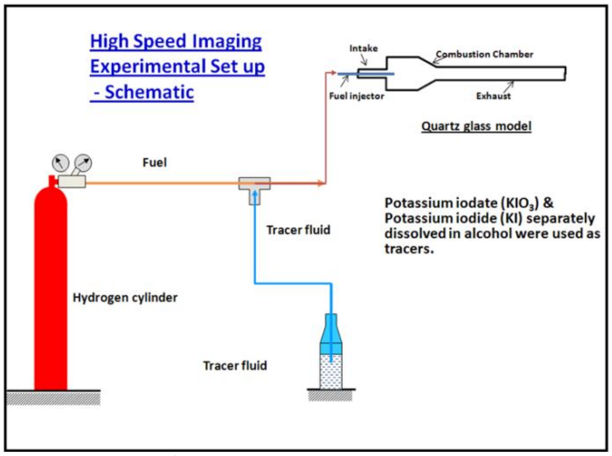


Fig. 4. Schematic of the test set up

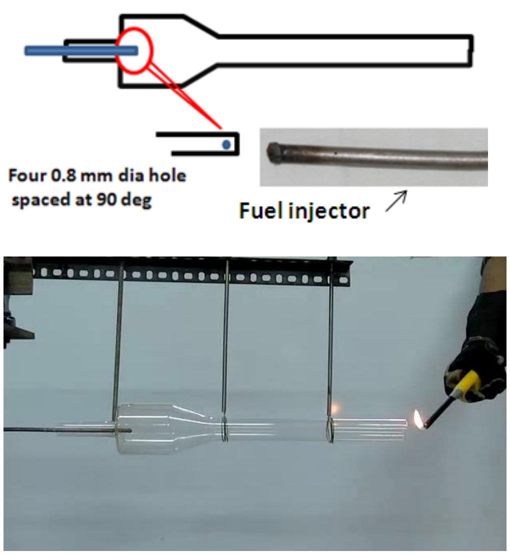


Fig. 5. Fuel injection scheme, quartz engine mounted on the test stand and ignition process

Fig. 6 shows the comparison of typical frames with and without a potassium iodide chemical tracer. The flame front frames clearly indicate the advantageous effect of injecting the tracer, thus helping to enhance the visibility of the hydrogen flame and track the movement of the heat release zones. A high-speed camera PHOTORON FAST CAM SA4 was used to capture the unsteady flow pattern. Time resolved frames were extracted to examine the flame front movement inside the engine.

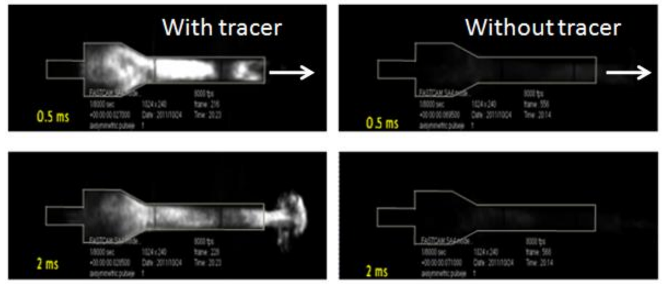


Fig. 6. Comparison of typical imaging frames with and without the potassium iodide chemical tracer.

## IV RESULTS, DISCUSSIONS AND CONCLUDING REMARKS

The main aim of this experimental investigation was to develop a non-intrusive optical technique and thereby gather a clear understanding of the flame front movement and mixing related heat release corresponding to resonant combustion inside an inline intake valveless pulsejet engine. Fig. 7 shows the time resolved frames of the flame front movement within the inline intake valveless engine. For the present study, imaging was carried out at 8000 frames per second with a resolution of 1024 x 240 pixels. The flame patterns clearly indicate the nature of the resonant combustion inside the pulsejet engine. The coherent structure of the combusted gases being discharged out in pulses and the downstream movement of each packet in stages is clearly seen. The movement of the heat release zones is also seen. Frame 1 shows the pocket of fuel air mixture ignited from the previous cycle being pushed out in pulse mode. The exhaust gases that are discharged from the tail pipe clearly show the formation of toroidal vortices (frames 2,3 & 4). The sucking of the hot gases back from the tail pipe into the engine because of the "Kadenacy effect" is clearly visible in the time resolved frame near the tail pipe (frame 5). Frame 6 gives an indication of mixing of fresh fuel / air mixture, with formation of vortices inside the combustion chamber which gets ignited from the residual hot gases sucked back. This clearly shows that the fresh fuel air mixture that is present in the combustion chamber during the suction phase gets successively ignited by this reverse flow of the residual hot gases thus eliminating the need for an ignition source except at the start.

The high-speed flame imaging technique has been successfully developed and is now being employed in developmental testing of valveless pulsejet engines to evolve a design methodology.

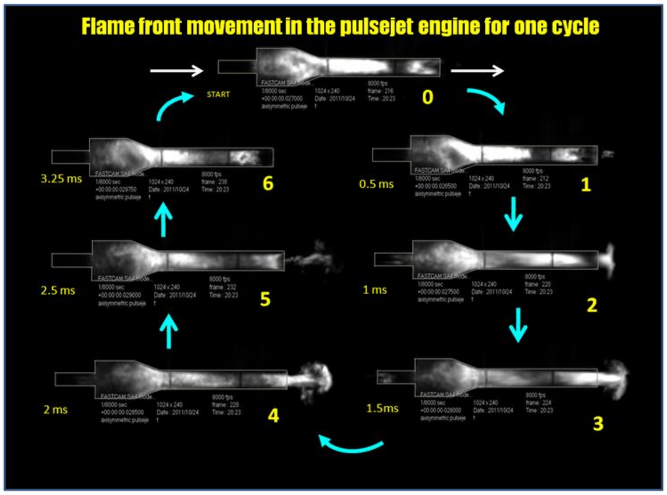


Fig.7. Time resolved frames of the flame front movement inside the inline intake valveless pulsejet engine for one cycle of sustained pulsation due to resonant combustion - potassium iodide chemical tracer

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